

Robotic Systems and Surgical Education

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ABSTRACT

This experimental study aimed at evaluating the efficiency of robots in the learning of surgical techniques. We recruited 40 surgeons, divided them into 2 groups of 20, each of which used the robotic system. The first group consisted of experienced physicians, and the second group comprised physicians in training. Each surgeon was allowed to use the da Vinci robotic system for 30 minutes twice in the span of 24 hours. The practice time period was divided into 15 minutes for tying and placement of sutures and 15 minutes for incisions and vascular suturing. We recorded the times required for the performances, and a statistically significant outcome was obtained. With variance analysis (ANOVA), it has been shown that the time needed to perform the exercises depends in a statistically significant way on the kind of test to be performed ($P < 0.01$), the experience of the surgeon ($P < 0.001$), and the kind of operation ($P < 0.025$). Robotic systems can be an optimal tool both for residents and experienced surgeons, for learning of basic surgical tasks and for perfection of clinical skills. The use of the system has great potential in surgical training, offering a reduction in the learning period, enabling checking for errors, and allowing an evaluation of the capabilities obtained. Final goals are a drastic reduction in the learning curve, a better technique, with a significant reduction in surgical errors and complications, with greater safety for the patient.

Key Words: Laparoscopy, Robotics, Surgical training.

INTRODUCTION

The development of modern technology, since the end of the second millennium, has contributed significantly to advancement in the field of surgery.^{1,2}

With the advent of new computer technologies, significant contributions have been made in both diagnostic and therapeutic procedures. Medical robotics is an emerging science that is acquiring ever-greater importance and acceptability in the field of surgery. This science is growing rapidly and offers enormous potential, which can bring significant improvements in clinical procedures for many surgical pathologies. We wish to emphasize that the use of robotics can offer new and innovative instruments for both teaching and learning.^{3,4}

Medical schools, scientific societies, and academic and clinical organizations are faced with the challenge of teaching, training, and assessing the level of competence of health professionals. Surgical training until the present time has been based traditionally on the use of models and on animals. These means, apart from being expensive, cannot offer repetition of surgical maneuvers. In addition, they are not particularly precise in simulating the clinical reality that the surgeon must face in the operating room.⁴⁻⁶

For this reason, it is necessary to make use of the advances that have been made in the area of computer science. In particular, with the use of the interactive graphics of advanced multimedia, virtual reality, and robotics, it is possible to obtain teaching instruments that are considerably less expensive, while offering a higher fidelity to the representation of the human anatomy. This offers the trainee a rapid learning experience without any risk to the patient.^{5,7}

THE GOAL OF THE RESEARCH

With this experimental study, we wished to evaluate the ability of surgeons who were not proficient in laparoscopic procedures, to learn some of the maneuvers necessary to perform a laparoscopic operation (ex, the insertion of sutures, tying of knots for the realization of the suture). For those surgeons who were experts in mini-

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invasive surgery, it was our intention to evaluate the modalities and the difficulties that the surgeon might be faced with in the performance of maneuvers that are normally done with classical laparoscopic instruments but are now replaced by a robotic device. By so doing, it was possible to appraise the ability of expert surgeons to learn new operational techniques. In addition, we wished to evaluate the ergonomics of the robotic system, while keeping in mind the fact that both the traditional and laparoscopic surgeons are often forced to assume nonergonomic positions or make unnatural wrist movements due to the limited range of motion of the laparoscope. Finally, we wished to study how the 3-dimensional optics of the robotic system can be used to better the visualization of the operational field.

With this experimental study, we wished to evaluate the efficacy of robotic training for surgical techniques and individualize any difficulties that might be encountered with the use of the machine.

METHODS

For experimental testing, we used the da Vinci robotic system (Intuitive Surgical, Inc. Sunnyvale, CA). This complex robotic system is composed of 2 main components: a control console and a surgical complex composed of 3 arms that are installed on an operating table.

The console has a 3-dimensional visualization system made of 2 monitors, one for each eye: the image is created with signals sent by 2 high-resolution fiberoptic cameras directed toward the operating field.

Fundamental elements of the console are the manipulators, which comprise the instruments that the operator acts with to activate the surgical elements of the robot arms. The pedal controls a damping system to reduce movements and eliminate tremor. The robot mechanism is made up of 3 mechanical arms.

Two of the robot arms serve for the manipulation of the surgical instruments; these 2 arms have 7 degrees of freedom. The third arm contains the optical system. The endoscope can have either a 0° or 30° lens applied. The entire apparatus is controlled by extremely complex software, which enables a simple use of the robot, on the part of the operator.

In our study, we had 40 surgeons use the da Vinci Robotic System.

We divided them into 2 groups to evaluate the efficacy of the robot as a surgical simulator.

The first group (given the name “senior”) was made up of surgical experts; the second group (“junior”) was composed of surgical residents.^{8–11}

The “senior” group comprised expert surgeons; the term “expert” was applied to those surgeons who had performed at least 200 laparoscopic operations as the main surgeon. These operations included both operations at the first level (eg, video-assisted laparoscopic cholecystectomy) and at the superior level (eg, left hemicolectomy). The “junior” group comprised first- and second-year surgical residents who had not performed any laparoscopic operation as the main surgeon. None of the members of either group had previously performed any robotic surgical procedures.

After having received a briefing on the functioning of the da Vinci Robotic System, each surgeon was allowed to use the system for 30 minutes on 2 different days. This time period was divided into 15 minutes to practice the placement and tying of sutures and 15 minutes to simulate the incision and the placement of vascular sutures.

During the exercise, the times needed to carry out the assigned tasks by the junior and senior surgeons were recorded.

Two different evaluations were performed during the execution of the test; one was quantitative (the time needed by both the senior and junior surgeons to carry out a given exercise were recorded), the other evaluation was one of quality. To evaluate the quality of the performances we applied the following criteria:

- The passage of a suture in an area of 5 mm² drawn on a support along with an adequate depth penetration of the tissue.
- The knot plane with 2 half knots, with subsequent determination of the strength of the suture.
- Continuous stitching, having a length of approximately 5 cm, with a blocked knot at the beginning and a blocked knot at the end, and the thread should have sufficient tension to approximate the margins.

Failure to achieve these characteristics is judged as a failure, and for this reason the trial exercise was considered not concluded within the allotted time period.

For the section on knots and suturing, the maximal time allowed was 180 seconds. Anything beyond that time was considered as a failure. *Major difficulty* was considered performance time between 136 and 180 seconds. *Slight difficulty* was considered completion times between 90

and 135 seconds, and *no difficulty* was completion of the task in less than 90 seconds. The organizers according to their experience in mini-invasive surgery and their use of the same da Vinci robotic system arbitrarily determined this categorization.

With regards to the simulation of a vascular suture, a time of >600 seconds was considered a failure, a time between 451 to 600 seconds was considered a major difficulty, times between 300 and 450 seconds as slight difficulty, and a time of <300 seconds as no difficulty. These time intervals were determined by similar criteria.

As for the subjective data given by each operator concerning the ease of use of the various commands, no objective criteria could be applied. Instead, each surgeon was asked his opinion concerning the overall ease of use of the manual commands, the visualization of the system, and the ergonomic position of the surgeon with the robotic system. The surgeon was asked to express his opinion using the terms, excellent, good, satisfactory, or unsatisfactory. The use of these 4 choices enabled us to have uniform subjective data by all the surgeons.

The data obtained were statistically evaluated according to:

- ANOVA (variance analysis),

- Loglinear (analysis of the table of contingency by means of a logarithmic linear model), and
- chi-square test (determines the significance of the tests, considers significant a test that has a value of $P < 0.05$).

RESULTS AND STATISTICAL ANALYSIS

The results obtained from this study are shown in **Tables 1 and 2** where the times (expressed in seconds) required by the participants are shown according to the type of exercise performed. Based on our experience with this robotic system, we have determined the time intervals that we felt were appropriate for the different exercises (**Table 3**). To compensate for unfamiliarity with the robotic system, the time intervals were increased by 50% of the time normally required by the average laparoscopist, having average experience, to perform similar operational maneuvers. These appropriate time periods were then applied to the participants to give the results shown in **Figures 1, 2, 3, and 4**.

By analyzing the results obtained, it was possible to determine the grade of difficulty of placing sutures and tying knots (**Figure 2**). During the first day of testing, 40% of the senior participants had no difficulty whatsoever, while another 40% had only slight difficulty. None of the senior

Table 1.
Suturing and Knot-tying Times (Seconds)

Juniors																				
Day 1	>240	142	153	152	201	103	118	139	164	99	138	149	168	124	175	99	114	95	102	159
Day 2	175	109	133	152	157	87	81	176	117	78	127	119	149	142	140	107	162	75	132	93
Seniors																				
Day 1	62	144	104	71	94	68	122	167	75	119	140	71	87	92	112	159	121	73	81	99
Day 2	69	108	86	69	99	77	96	116	72	69	104	79	74	79	70	111	88	77	72	81

Table 2.
Incision and Suturing Times (Seconds)

Juniors																				
Day 1	>720	490	511	582	>720	498	502	>720	667	411	702	471	561	472	654	484	506	359	459	489
Day 2	709	399	407	598	591	537	410	699	588	317	577	549	502	361	582	338	529	304	344	504
Seniors																				
Day 1	291	582	441	227	469	326	439	653	285	401	509	292	334	281	374	661	417	287	316	461
Day 2	247	438	291	255	427	291	315	527	288	379	406	225	371	266	296	555	309	271	277	399

Table 3.
ANOVA Results

Group	Mean	SD
Stitches and Knots		
Senior	93.93	18.83
Junior	133.63	5.54
Incision and Suturing		
Senior	373.10	17.72
Junior	520.58	4.11

participants were unsuccessful. In the case of the junior participants, 40% had slight difficulty, 50% had significant difficulty, and 10% were unsuccessful.

On repeating the test on the next day, none of the junior surgeons were unsuccessful, those with significant difficulty declined to 40%, those with slight difficulty remained unchanged at 40%, but those with no difficulty whatsoever increased to 20%. In the case of the senior surgeons,

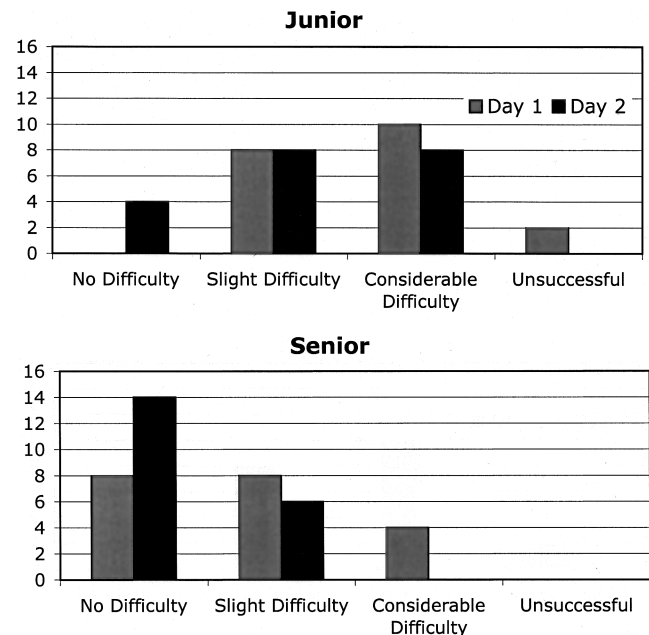


Figure 2. Passage of sutures and the tying of knots: improvement in learning between the first and second day.

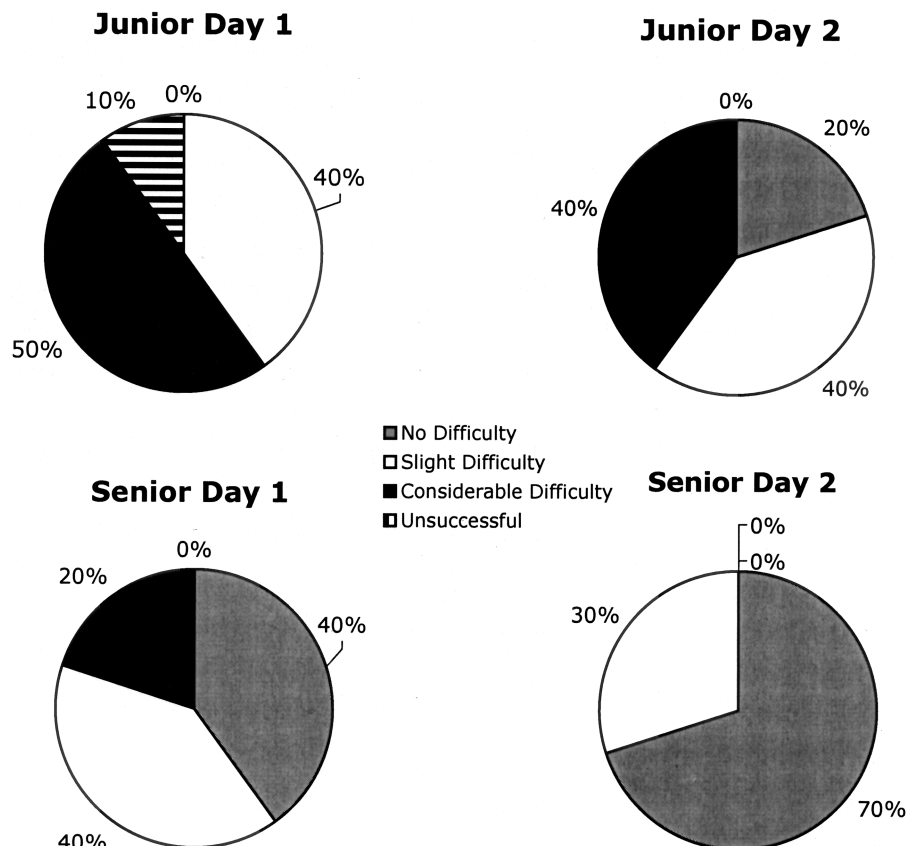


Figure 1. Difficulty in the passage of sutures and the tying of knots.

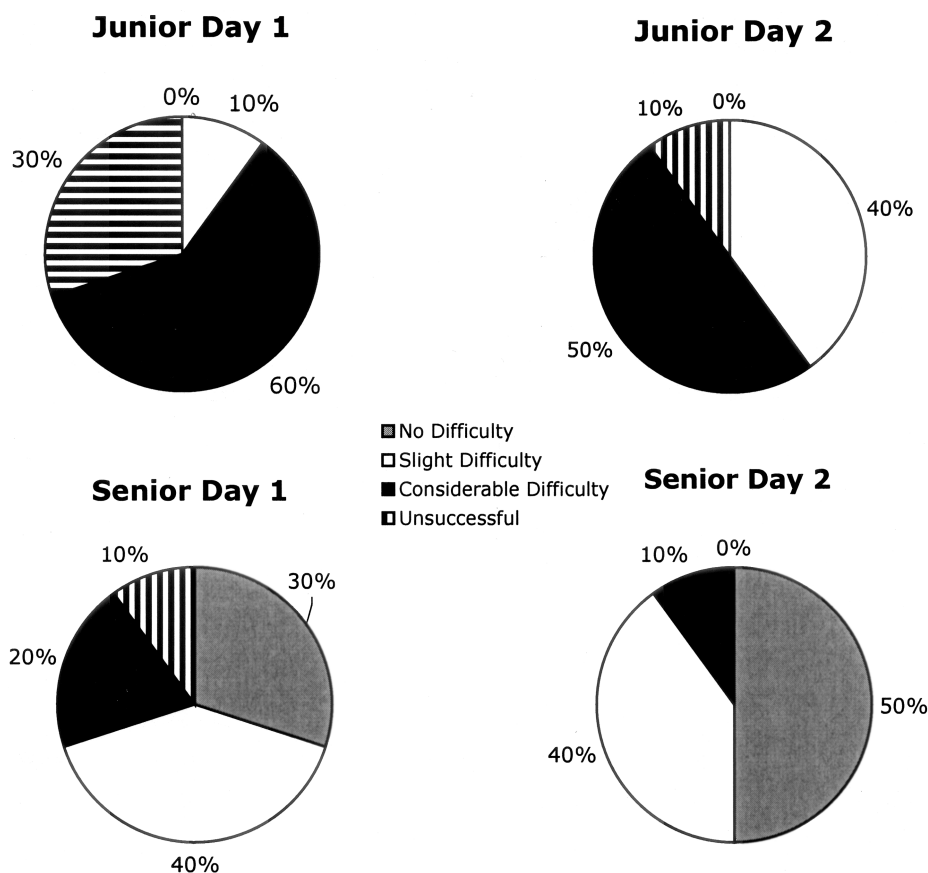


Figure 3. Difficulty in making the incision and subsequent suturing.

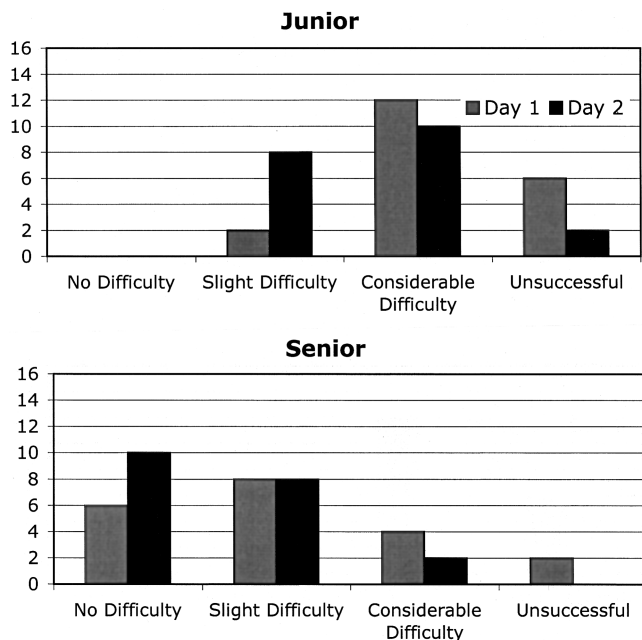


Figure 4. Making the incision and subsequent suturing: improvement in learning between the first and second day.

the number of participants who had no difficulty increased demonstrably from 40% to 50%, while the number of participants with slight difficulty declined from 40% to 30%.

During the second trial, none of the senior participants had either significant difficulty or any failures.

The second exercise consisted of the incision and the subsequent placement of sutures in a green string bean, simulating an arterial vessel (**Figure 4**). In the group of senior participants, on the first trial, 30% had no difficulty, 40% had slight difficulty, and 20% had considerable difficulty, and 10% of the participants were unsuccessful. Of the junior participants on the other hand, 10% had slight difficulty, 60% had significant difficulty, and 30% were unsuccessful. On the second day of the trial, the number of unsuccessful participants in the junior group declined from 30% to 10%, those with significant difficulty decreased from 60% to 50%, and the number of those with slight difficulty increased from 10% to 40%.

After the second test, the senior participants had no fail-

ures; the number of those with significant difficulty declined from 20% to 10%, while simultaneously those with no difficulty rose from 30% to 50%. This descriptive evaluation of the data was reinforced by the statistical evaluations performed with the various tests.

With the variance analysis (ANOVA) (**Table 4**), which allows one to determine the significance of the difference between the arithmetic averages, it was determined that the amount of time necessary to carry out the proposed exercises depended, in a statistically significant way, on the type of exercise to be performed ($P<0.01$) and by the experience of the operator ($P<0.001$).

Evaluation with the loglinear test provided similar results, in that the amount of time used depended, in a statistically significant way, on the experience of the operator ($P<0.001$) and the type of exercise performed ($P<0.025$). These 2 variables, the experience of the operator and the exercise performed, have an additive effect on the time required ($P<0.01$).

The difference in the time used between the first and second day was also studied for both the junior and the senior participants.

In the analysis of the results for suturing and knot tying, the results were significant for the senior participants ($P=0.057$) and just below the significant level ($P=0.097$) for the junior participants. In the second procedure, which involved the incision and suturing of the string bean, the improvement in performance was significant for the junior group ($P=0.055$) but not so for the senior group ($P=0.205$).

At the end of each trial period, a test was made to evaluate the "maneuverability" of the robot. This term means the

ease of interaction of the participants with the robot, from an ergonomic point of view, in the performance of the surgical movements during the simulation.

This has to do with a completely subjective evaluation by a homogenous group of subjects that are all involved in the performance of the same surgical procedure (**Figures 5 and 6**).

The results of the maneuverability test were as follows: on the first day, 40% of the senior participants had judged the maneuverability of the robot to be excellent, and a remaining 50% judged it as being good. In particular, the 3-dimensional optical system was particularly appreciated by the surgeons, due to its ability to reproduce the operational field in video-assisted surgery, which is comparable to that seen with traditional surgery; the ergonomic positioning with the operational console was rated good, while many had initial difficulty with the controls that regulate the movements of the effector arm.

The junior participants instead judged maneuverability as only sufficient in 40% of the cases and as excellent in 10%. In particular, they rated the ergonomic position of the surgeon at the console as allowing excellent and good interaction with the controls that regulate the effector arm; few judged the 3-dimensional optical system as useful for performing the maneuvers in the simulation surgery. This was in contrast with the prior group and was interpreted as being due to their inexperience with laparoscopic surgery, which as a consequence did not allow them to make an adequate comparison between the 2 visual systems. On the contrary, on the second day, the number of junior participants stating that maneuverability was excellent increased from 10% to 40% along with a corresponding decrease in those that considered the maneuverability as being only sufficient, from 40% to 20%.

For the senior surgeons, passing from the first to the second trial day, their acceptance of the machine was shown by an increase from 40% to 80% of those who rated the maneuverability as being excellent. The remaining 20% rated it as being good. Analyzing these data with the loglinear test confirmed these results. In effect, it showed that the maneuverability depends in a significant way on the years of experience that the surgeon has in his career ($P<0.001$) as well as the number of trials that were performed ($P<0.01$).

By means of the log test, it was possible to show the added effect of 2 variables, experience and the number of trials performed, on maneuverability. These factors are not independent but rather act in harmony, adding their

Table 4.

Difficulty Level According to Time Interval

Difficulty Level	Time Interval (Seconds)
Passing Stitches and Tying	
No Difficulty	<90
Slight Difficulty	90–135
Considerable Difficulty	136–180
Unsuccessful	>180
Incision and Subsequent Suturing	
No Difficulty	<300
Slight Difficulty	300–450
Considerable Difficulty	451–600
Unsuccessful	>600

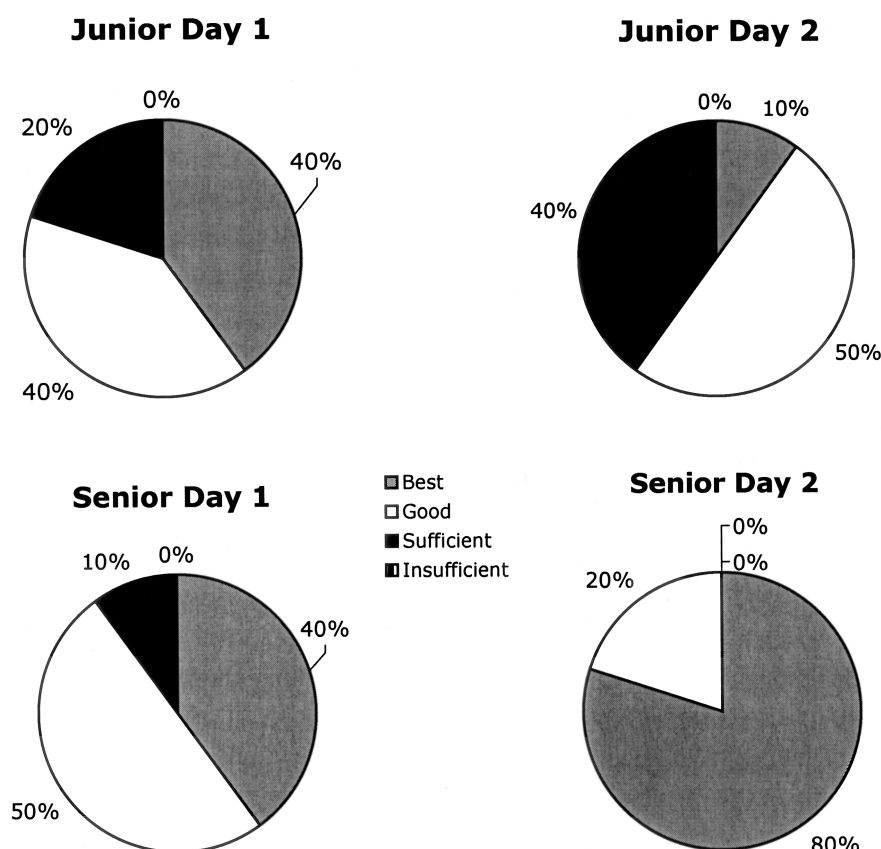


Figure 5. Maneuverability of commands.

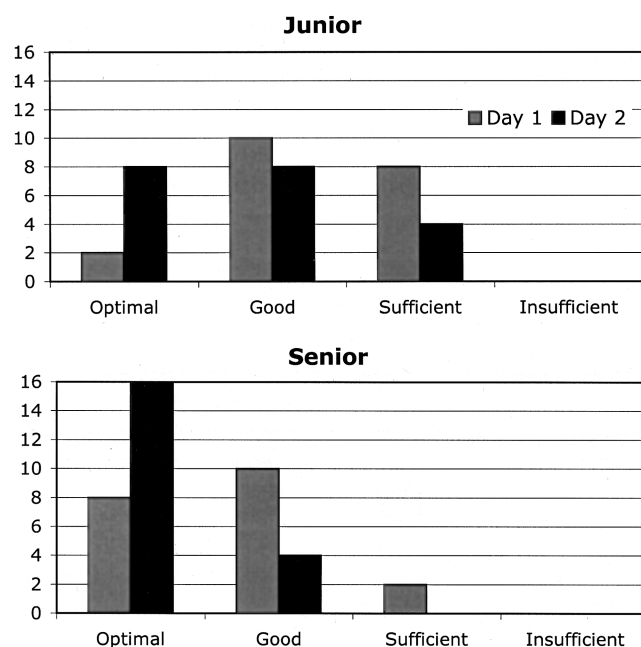


Figure 6. Improvement in maneuverability between Day 1 and Day 2.

effects on the capability to maneuver and interact with the robot.

Also with regard to the maneuverability of the command controls, we compared the data obtained from the 2 groups of surgeons during the 2-day test period. In this way, it was apparent that the increase in the maneuverability between the first and second day was statistically significant ($P=0.0268$) for the senior surgeons, while it was just under the significance level ($P=0.075$) for the junior surgeons.

DISCUSSION

The evolution of surgical robots along with the recent developments in information technology has opened up new horizons in both the teaching and the surgical training fields.^{12,13}

With the improvements in the image generator techniques used in the generation of multimedia virtual reality and the progressive reduction in the costs of technological processes, it has been possible to develop dedicated sys-

tems for the teaching of anatomy, as well as the physiology and pathology in a virtual environment.^{1,3,14,15} This in turn can be applied in the simulation of surgical procedures.^{16–18}

This offers the possibility of training health care personnel in a simulated environment, thereby allowing one to perfect one's skills, and determining the proficiency of a surgeon in performing a given operation.

From our experience, it has become apparent that robotic surgical simulation is an optimal training instrument and can be used by both young surgeons in training, for learning basic surgical techniques, and the veteran surgeon for practicing complex surgical maneuvers, some of which may not be considered routine.

Thanks to the robot simulators that integrate appropriate software, it is possible to simulate delicate operations to allow the surgeon to correct any eventual technique errors and thereby gain self-confidence.^{19,20} The senior surgeons demonstrated greater difficulties initially in adapting to the control console; however, this was readily overcome when they realized that the robot required the same hand movements as they would normally perform during the course of a hands-on operation. In fact, our experience has shown that the senior surgeons found the robot device to be quite intuitive, and in fact those surgeons with the greatest surgical experience were able to adapt to this robot device more quickly than their junior counterparts did.^{14,21}

This is of fundamental importance in that it means that the more experienced surgeons adapt more readily to this new device, thereby allowing them to acquire new therapeutic and diagnostic procedures.

The already expert surgeon, in an attempt to offer the most recent therapeutic possibilities to his patients, will not find the same difficulty as that which he had to deal with in the mini-invasive surgical procedures.^{22,23}

For the senior surgeon, the robot is an important training instrument that can be used to sharpen one's own technique and to learn new procedures as well.^{19,24}

Evaluation of junior surgeons revealed that they had greater difficulty with this new approach. This could be attributed to their lack of clinical experience, which prohibits them from acting with the same self-assuredness as those with more years of experience. This is reflected in the way they interact with the technologically advanced control system. This does not negate the fact that the junior surgeons appreciate the benefits the robot offers

them as a learning tool. They have noted an improvement in their surgical technique after only a few sessions with the apparatus.²⁵

For the junior surgeon, the robot system is a valid aid in learning the fundamentals of a surgical procedure thus helping them gain confidence with surgical maneuvers and allowing the acquisition of the manual dexterity, which, in the end, allows the surgeon to operate with maximum security to the patient.²⁶

An important point that we must consider is the increased efficiency in the procedures performed in the 2 groups after the 2-day trial period was concluded.

From these data, we can conclude that the robot system is an efficacious simulator that allows significant improvement in the learning phase in only a few sessions. This is true for the junior group: when they were able to acquire greater confidence with the system they were able to recuperate their deficiencies in manual dexterity. It is also true for the senior group: even though they were less familiar with the sort of video game-like control panel, they are able to take advantage of the physical skills acquired with years of traditional surgical experience.^{19,24}

Surgical simulation through robotic technology can reproduce a desired situation, thereby permitting rapid learning.^{25,27}

The fundamental requirements of a surgical simulation system are the ability to repeat a given action or procedure; a sensory feedback system that enables a lifelike physical and physiological response that the operator has to the internal organs; the use of the same surgical instruments that are normally used in the operation; and the possibility to simulate emergency situations and various surgical procedures.^{15,28}

The performance of this procedure, based on a simulation system, is extremely efficacious in reducing the learning period, allowing continuous feedback on errors made, along with the possibility of recording the level of competence obtained so as to verify the level of performance of the person carrying out the simulation.^{24,26}

The learning curve becomes evident whenever an accident occurs that could place the life of the patient at risk. To avoid this possibility, it is necessary to take advantage of all means currently offered by advanced virtual reality multimedia, computer science, and robotic technology. By so doing, one can obtain simulators that are simple and intuitive to use and will have a limited impact on health costs.^{19,29}

A problem that must be overcome to have a perfect simulation is to generate a feedback system that accurately reproduces the real anatomical environment, with all its physiological as well as pathological variations that are possible in clinical practice. Other problems include the movements and vibrations that organs can have due to the effect of blood pressure, and cardiac pulsations, spasms, and reflex contractions can also place large limitations on the true simulation of the human body.^{16,29,30}

Finally, it is difficult to render a simulation of the response (cut, pinch, push, retract) of different tissues to external forces created by the action of the instruments used (scissors, clamps), because elastic tissue will respond differently from fibrotic tissue.^{18,19,28}

The future endeavors in the development of surgical simulators will be directed toward integrating robot technology to that of virtual reality.³¹ Virtual reality in surgical simulation, as is seen in flight simulators, could allow the young physician to interact with an imaginary human body so as to learn the surgical anatomy and specific diagnostic, or therapeutic, or both diagnostic and therapeutic, procedures.¹⁵

In this virtual world of 3-dimensional imagery, the surgeon can explore the 3-dimensional anatomy of various organs as if they really exist. This level of reality can be further amplified by the incorporation of animated graphics, and the images of CAT and MRI scans could allow an even further, more realistic, representation of the natural world.^{17,29,31}

CONCLUSION

Robotics together with the development of new technologies can allow the training of health care personnel to be carried out in a simulated environment, so that perfection of surgical technique can be obtained without causing any harm or exposing the patient to any risk.^{4,19,20}

The robotic system has been shown to be an instrument that can be easily utilized, even by those who have never used one.

In our study, it was shown that experts in mini-invasive surgical techniques perform well using the robotic system in those exercises that correspond to the same movements used with classical laparoscopic instruments. The new technology was not perceived as an obstacle, as is evidenced by the objective evaluation of time intervals and by the subjective evaluation of the ease of handling.

The residents-in-training have shown a greater ability to

interact with the new instruments, demonstrating the capacity to rapidly learn elementary surgical maneuvers. The difficulties encountered by the residents-in-training and by their instructors who recorded the time intervals were deemed much less when compared with those experienced while learning with classical laparoscopic instruments.

This, even if our experience is limited to a few exercises, is believed to be a positive indicator regarding the ease in learning how to use the machine and also regarding the drop in the amount of time needed for learning new surgical procedures.

One could compare the learning curves of surgeons-in-training obtained while performing surgical procedures (ex, cholecystectomy) utilizing both traditional laparoscopic instrumentation with the learning curves when using a robotic technique.

Our experience has shown that robots are an excellent teaching aid that can be useful to both the experienced surgeon, in the fields of traditional as well as in laparoscopic techniques, and the physician in training. This means allows the improvement of surgical technique and the acquisition of new methods of diagnosis and care. It has been shown that both groups of participants intuitively were able to interact with the robot, reproducing the surgical maneuvers. The participants also demonstrated enthusiasm for this learning procedure, after having found a significant improvement in their performance after only a few practice sessions with the robot device.^{1,2,32}

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